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Altérations provoquées par les radiations ionisantes  
dans les cellules sexuelles des végétaux supérieurs  
et manifestations génétiques de ces altérations

## ARTICLE PRINCIPAL

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## An approach to the study of genetic effects from the $^{14}\text{N}(\text{n}, \text{p})^{14}\text{C}$ reaction for thermal neutrons

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The genetic effect of the nuclear reaction  $^{14}\text{N}(\text{n}, \text{p})^{14}\text{C}$  was evaluated in a tomato cross; dry pollen with a known chemical composition was exposed to a thermal neutron flux of  $4.1 \times 10^7 \text{ n cm}^{-2} \text{ sec}^{-1}$  plus 11.6 rads/h gamma contamination.

For this purpose plants were fed  $^{15}\text{N}$  in place of  $^{14}\text{N}$  from the beginning of growth.

For seven criteria of radiosensitivity (reduction in seed-set and mutation frequencies in  $F_1$ ) the radiation effect was reduced by half to two-thirds as a consequence of this change.

As the second capture reaction,  $^{10}\text{B}(\text{n}, \alpha)^7\text{Li}$ , was similarly controlled in the same material, the degree of genetic effect of both reactions could be compared. They were found to be independent and additive, the nitrogen capture reaction being the more important, partially because of a larger effect per rad.

The gamma component of the beam also provided a basis for an estimation of RBE. This would lie, for the  $^{14}\text{N}$  reaction, in the neighbourhood of 1.5 to 3.0 in the present conditions.

### 1. Introduction

Two nuclear capture reactions,  $^{14}\text{N}(\text{n}, \text{p})^{14}\text{C}$  and  $^{10}\text{B}(\text{n}, \alpha)^7\text{Li}$ , are the main sources of energy dissipated in a small sample of biological material exposed to thermal neutrons (Conger and Giles 1950).

The contribution of the second reaction was studied in plants (Conger 1953, Matsumura, Kondo and Mabuchi 1963, Moutschen, Moutschen-Dahmen, Woodley and Gilot 1969) by adding extra natural boron or pure  $^{10}\text{B}$  to tissues. A more direct approach was recently suggested (Ecochard and Oosterheert 1966, Ecochard and de Nettancourt 1967, 1969, Ecochard 1968) based on the replacement of normal boron by either  $^{10}\text{B}$  or  $^{11}\text{B}$ . It was then found that:

(1) The difference in radiosensitivity to thermal neutrons between plants given the two treatments is about 30 per cent and may vary to some extent according to the site of induced damage.

(2) Calculation of what this difference would be for an homogeneous distribution of the absorbed energy within the cell suggests a greater boron concentration at the cell periphery.

A similar approach can be used to investigate the contribution of the  $^{14}\text{N}(\text{n}, \text{p})^{14}\text{C}$  reaction, as natural  $^{14}\text{N}$  can be replaced by  $^{15}\text{N}$ , which has a negligible cross-section for thermal neutrons:  $2 \times 10^{-5}$  against 1.75 barn. The expected result would be a decrease in sensitivity, in proportion to the biological

† Contribution No. 562 of the Biology Division of Euratom.

effect of this reaction. If the N and B content of the irradiated cells can be determined, the respective roles of the two major nuclear reactions can be evaluated and compared. Such was the aim of the experiment reported here.

## 2. Materials and methods

The experimental conditions of the present study were similar to those described by Ecochard and de Nettancourt (1969): radio-induced injuries were scored in  $F_1$  hybrids of two genetically-different tomato strains. The pollinator plants, dominant for three marker genes, were grown on pure stable isotopes of nitrogen and boron (see below) and pollen was applied after irradiation to pistillate flowers of the recessive partner.

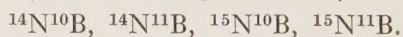
A daily defoliation was carried out on the staminate plants (*Lycopersicon esculentum*, cv Moneymaker). By this method (de Zeeuw 1954, Bijleveld and de Zeeuw, unpublished) they remain very small and flower 2 weeks earlier, so that 1.2 g nitrogen (14 litre nutrient solution) is sufficient for 50 plants until full flowering of the first two inflorescences.

Nitrogen, either natural or enriched (supplied by O.N.I.A., France) to 97.4 per cent  $^{15}\text{N}$  was provided as nitric acid in a solution adjusted to neutrality of:

|                               |      |                     |
|-------------------------------|------|---------------------|
| $\text{HNO}_3$                | 6    | millimole per litre |
| KOH                           | 3.5  |                     |
| $\text{Ca}(\text{OH})_2$      | 1.75 |                     |
| $\text{Mg} \cdot \text{SO}_4$ | 1.75 |                     |
| $\text{H}_3\text{PO}_4$       | 1    |                     |

Boron was introduced as boric acid (2.86 p.p.m.) enriched (supplied by Quartz et Silice, France) to 91 per cent and 5 per cent  $^{10}\text{B}$ , respectively. The other trace elements were as in formula (2) of Hoagland-Arnon (1950).

The four treatments (50 defoliated plants each) were thus:



At four successive times, pollen of the various treatments was separately collected and pre-treated at room temperature in vacuum and then in a dry mixture of  $\frac{1}{5}\text{O}_2$  and  $\frac{4}{5}\text{N}_2$  in sealed Teflon tubes of 4 ml. A cellophane disc covered the pollen to protect it against proton induced in the surrounding gas during irradiation.

On each occasion the four tubes of pollen were then exposed together for 48 hours at  $20^\circ\text{C}$  to a flux of  $4.1 \times 10^7 \text{ n}_{\text{th}} \text{ cm}^{-2} \text{ sec}^{-1} \pm 3$  per cent in the BARN reactor at Wageningen. The contamination by gamma-rays, including the  $\text{H}(\text{n}, \gamma)\text{D}$  capture reaction, was 11.6 rads/h at the level of the tubes.

Emasculated plants of *L. esculentum* strain 121 (origin Brock and Franklin) grown in the usual manner were pollinated immediately afterwards.

All the material was kept at optimum temperature of  $23^\circ\text{C}$  for a 16-hour period (20 000 lux) and  $17^\circ\text{C}$  for the 8-hour dark period. Relative humidity was maintained at 50–60 per cent.

In the  $F_1$  generation after the above cross, the three seedling marker genes would be heterozygous,  $\text{Hl} \cdot \text{hl}$  (hairiness),  $\text{A}_1\text{a}_1$  and  $\text{A}_w \cdot \text{a}_w$  (presence of anthocyanin), so that any recessive mutation induced at one of these loci in the

irradiated pollen is readily detectable. Further mutations, for chlorophyll and morphology, were also observed. In total, seven criteria of sensitivity were scored: the reduction in seed-set, i.e. number of seeds per fruit in control minus irradiated, the frequency of mutant individual per 100 germinating seeds, the frequency of mutations for anthocyanin, hairiness, chlorophyll, morphology, and the total frequency of mutations.

Control pollen, collected and pre-treated in the same way but not irradiated, was used in three replicates to determine the normal seed-set and spontaneous mutation frequencies.

A sample of it was also submitted to chemical analysis for N, C, H, O and B (table 1).

|                                            |                    |
|--------------------------------------------|--------------------|
| Weight of pollen collected for analysis:   | 0.602 g            |
| Weight of this pollen after pre-treatment: | 0.577 g            |
| Chemical composition:                      | C: 46.07 per cent  |
|                                            | O: 32.07 per cent  |
|                                            | N: 9.28 per cent   |
|                                            | H: 7.31 per cent   |
|                                            | B: 26.6 p.p.m.     |
|                                            | ash: 5.27 per cent |

Table 1. Chemical composition of the tomato pollen used for irradiation. C, H, O, N and ash measurement: Laboratoire de Police Municipale, Paris. Boron content determined at the laboratory by curcumin colorimetric method.

### 3. Results

#### 3.1. Estimation of the absorbed doses

The energy released by a given capture reaction and absorbed in the tissues is expressed in  $\text{erg g}^{-1} \text{sec}^{-1}$  by the relation:

$$W = \phi \times \Sigma \times A \times E \times F.$$

$\phi$  = neutron flux in  $\text{n cm}^{-2} \text{sec}^{-1}$ ,

$\Sigma$  = cross-section in  $\text{cm}^2 = \sigma$  in barn  $\times 10^{-24}$ ,

$A$  = number of atoms of the reacting isotope per g of fresh tissue

= proportion in percentage of weight  $\times$  Avogadro No.  $\times$  atomic mass $^{-1}$ ,

$E$  = energy in erg released by one reaction

= specific energy in MeV  $\times 1.602 \times 10^{-6}$ ,

$F$  = fraction of energy absorbed in the cell (assumed to be 1 for charged particles).

The energy in rad absorbed during the 48-hour exposure is then

$$\text{dose} = W \times 10^{-2} \times 172800.$$

Table 2 gives the data for calculation with both nitrogen isotopes, both boron isotopes and natural boron as standard (19.8 per cent  $^{10}\text{B}$  + 80.2 per cent  $^{11}\text{B}$ ).

|                                                                    | Natural<br>N | Enriched<br><sup>15</sup> N | Enriched<br><sup>10</sup> B | Enriched<br><sup>11</sup> B | Natural<br>B |
|--------------------------------------------------------------------|--------------|-----------------------------|-----------------------------|-----------------------------|--------------|
| Proportion in active isotope ( <sup>14</sup> N or <sup>10</sup> B) | 0.996        | 0.026                       | 0.91                        | 0.05                        | 0.198        |
| Cross-section in barn                                              | 1.75         | 1.75                        | 3840                        | 3840                        | 3840         |
| Number of active atoms per g material $\times 10^{-18}$            | 3980         | 103.7                       | 1.348                       | 0.07404                     | 0.2932       |
| Specific energy in erg $\times 10^6$                               | 1.002        | 1.002                       | 3.749                       | 3.749                       | 3.749        |
| Energy absorbed in erg per g per sec                               | 0.2861       | 0.007456                    | 0.7956                      | 0.04370                     | 0.1730       |
| Energy in rads absorbed in 48 hour exposure                        | 495          | 13                          | 1376                        | 75                          | 299          |

Table 2. Components of the energy absorbed for various nitrogen and boron treatments, as derived from chemical and isotopic composition, and from physical characteristics of the capture reactions. Thermal neutron flux:  $4.1 \times 10^7 \text{ n cm}^{-2} \text{ sec}^{-1}$ .

The components of the absorbed dose were thus estimated as:

$D_N = 495$  or 13 rads for respective nitrogen isotopes,

$D_B = 1376$  or 75 rads for respective boron isotopes, and

$D_\gamma = 299$  rads for natural boron.

### 3.2. Estimation of the biological effects

The observed radiation effects are presented in table 3, as arithmetic averages of the four replicates.

A significant difference between replicates, similar for all criteria, was found, which was not entirely due to the differences in size between the populations; the fourth replicate exhibited a lower value for radiosensitivity in every case. No explanation for it could be given.

Despite this difficulty, table 3 and the general trend in each replicate demonstrate the following:

(1) For all criteria the four treatments follow the order:

$$\text{effect } ^{15}\text{N}^{11}\text{B} < \text{effect } ^{15}\text{N}^{10}\text{B} < \text{effect } ^{14}\text{N}^{11}\text{B} < \text{effect } ^{14}\text{N}^{10}\text{B},$$

which shows an influence of the nitrogen and of the boron reactions, the former being more important than the latter.

(2) For all criteria, except seed-set expressed in arithmetic values:

$$\text{effect } ^{15}\text{N}^{10}\text{B} - \text{effect } ^{15}\text{N}^{11}\text{B} \sim \text{effect } ^{14}\text{N}^{10}\text{B} - \text{effect } ^{14}\text{N}^{11}\text{B},$$

$$\text{effect } ^{14}\text{N}^{11}\text{B} - \text{effect } ^{15}\text{N}^{11}\text{B} \sim \text{effect } ^{14}\text{N}^{10}\text{B} - \text{effect } ^{15}\text{N}^{10}\text{B}.$$

Again, after logarithmic transformation of the original data for seed-set, these relations fitted.

This means that the two components of the neutron capture process can be considered as independent and additive, as was further confirmed at 0.5 probability level by covariance analysis.

|                                          | Treat-<br>ment<br>$^{15}\text{N}^{11}\text{B}$ | Treat-<br>ment<br>$^{15}\text{N}^{10}\text{B}$ | Treat-<br>ment<br>$^{14}\text{N}^{11}\text{B}$ | Treat-<br>ment<br>$^{14}\text{N}^{10}\text{B}$ | Standard<br>deviation |
|------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|-----------------------|
| Total seeds harvested (control 8481)     | 7241                                           | 5377                                           | 2286                                           | 1394                                           |                       |
| Seeds germinating (control 5598)         | 4595                                           | 3218                                           | 778                                            | 837                                            |                       |
| Reduction in seed-set,<br>original data† | 50.7                                           | 59.1                                           | 72.1                                           | 74.3                                           |                       |
| (1) Reduction in seed-set‡               | 1.1 1.08                                       | 1.4 1.41                                       | 2.5 2.51                                       | 2.9 2.83                                       | 0.22                  |
| (2) Frequency of mutant<br>individuals§  | 3.1 3.41                                       | 5.2 4.90                                       | 8.1 7.85                                       | 9.0 9.34                                       | 1.24                  |
| (3) Mutation frequency:<br>anthocyanin   | 1.3 1.43                                       | 1.8 1.73                                       | 3.2 3.15                                       | 3.3 3.45                                       | 0.85                  |
| (4) hairiness                            | 0.4 0.44                                       | 0.8 0.76                                       | 1.0 0.99                                       | 1.3 1.31                                       | 0.22                  |
| (5) chlorophyll                          | 1.3 1.29                                       | 1.8 1.86                                       | 4.0 4.01                                       | 4.5 4.59                                       | 0.83                  |
| (6) morphology                           | 1.2 1.16                                       | 2.4 2.45                                       | 3.5 3.60                                       | 4.9 4.89                                       | 0.92                  |
| (7) Total mutation frequency             | 4.3 4.63                                       | 6.9 6.54                                       | 12.9 12.64                                     | 14.3 14.56                                     | 2.29                  |

Table 3. Irradiation effect in the four treatments, means of four replicates corrected for control. For the seven criteria of radiosensitivity: left, observed data; right, estimated values based on the assumption of independence and additiveness for nitrogen and boron effects.

† Number of seeds per fruit in control minus irradiated treatment.

‡  $-\log$  (number of seeds per fruit in irradiated treatment over control).

§ Criteria 2 to 7: frequency per 100 germinating seeds.

### 3.3. Dose-effect relationship

With low doses and low dose-rates, the dose-effect relationship can be considered linear in a first approximation (see discussion). Therefore the model which will be used to express the effect as a function of the dose of each component of the beam is:

$$\left. \begin{aligned} \text{effect } ^{15}\text{N}^{11}\text{B} - \text{control} &= 557k_{\gamma} + 13k_{\text{N}} + 75k_{\text{B}}, \\ \text{effect } ^{15}\text{N}^{10}\text{B} - \text{control} &= 557k_{\gamma} + 13k_{\text{N}} + 1376k_{\text{B}}, \\ \text{effect } ^{14}\text{N}^{11}\text{B} - \text{control} &= 557k_{\gamma} + 495k_{\text{N}} + 75k_{\text{B}}, \\ \text{effect } ^{14}\text{N}^{10}\text{B} - \text{control} &= 557k_{\gamma} + 495k_{\text{N}} + 1376k_{\text{B}}, \end{aligned} \right\} \quad (1)$$

where  $k_{\gamma}$ ,  $k_{\text{N}}$  and  $k_{\text{B}}$  are the respective effects induced per rad by gamma rays, or the capture reaction in nitrogen or in boron.

To estimate the coefficients  $k_{\gamma}$ ,  $k_{\text{N}}$  and  $k_{\text{B}}$ , this system of equations was solved by the method of least squares, so that the estimated radiation effect in the four treatments could be calculated (table 3).

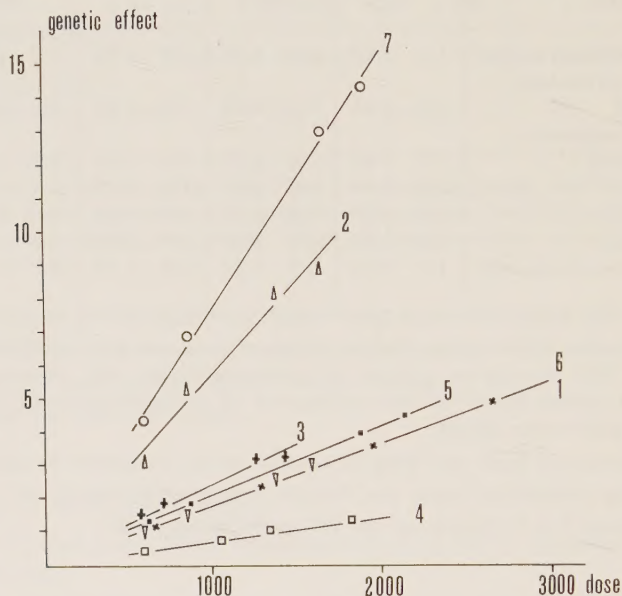
The coefficients  $k_{\gamma}$ ,  $k_{\text{N}}$  and  $k_{\text{B}}$  are represented in table 4 with their standard deviations.

The dose-effect relationship can now be tentatively represented in a graphic form by plotting as abscissa the dose of pure gamma needed to produce the same

effects as the actual beam (terms on right of equation (1) divided by  $k_\gamma$ ). This representation is given in the figure.

The graph indicates that the contribution of the capture reactions in the more efficient treatment,  $^{14}\text{N}^{10}\text{B}$ , is 1.5 to 4 times as great as the gamma component.

The slope of the lines, i.e. effect per rad gamma is minimum at the specific Hl locus (hairiness):  $7 \times 10^{-4}$  mutation per cent, and reaches  $7.7 \times 10^{-3}$  for total mutations.



Relationship between genetic irradiation effect and dose, expressed in rad of gamma, equivalent to the actual beam.

- (1) reduction in seed-set;
- (2) frequency in mutant individuals;
- (3) mutation frequency: anthocyanin;
- (4) hairiness;
- (5) chlorophyll;
- (6) morphology;
- (7) total mutation frequency. Units as in table 3.

### 3.4. Relative efficiency of the dose components

Table 4 shows that for all criteria  $k_N$  is much higher, average 8 times as much as  $k_B$ , which stresses the prominent influence of nitrogen in thermal neutron sensitivity.

The effect of both capture reactions is probably larger for the non-specific mutations, chlorophyll and morphology, than for the specific ones, anthocyanin and hairiness.

Finally, in order to evaluate from a practical point of view how much control of the nitrogen or boron isotopic composition can influence radiosensitivity, the

|                                        | Regression coefficients:<br>effect per rad ( $\times 10^3$ ) |                  |                 | $\frac{k_N}{k_\gamma}$ | $\frac{k_B}{k_\gamma}$ |
|----------------------------------------|--------------------------------------------------------------|------------------|-----------------|------------------------|------------------------|
|                                        | $k_\gamma$                                                   | $k_N$            | $k_B$           |                        |                        |
| (1) Reduction in seed-set              | $1.84 \pm 0.62$                                              | $2.96 \pm 0.21$  | $0.25 \pm 0.08$ | $1.61^\dagger$         | $0.14^\dagger$         |
| (2) Frequency of mutant individuals    | $5.76 \pm 3.29$                                              | $9.21 \pm 1.84$  | $1.14 \pm 0.69$ | $1.60^\ddagger$        | $0.20^\ddagger$        |
| (3) Mutation frequency:<br>anthocyanin | $2.45 \pm 2.29$                                              | $3.58 \pm 0.87$  | $0.23 \pm 0.32$ | 1.46                   | 0.09                   |
| (4) hairiness                          | $0.73 \pm 0.57$                                              | $1.14 \pm 0.32$  | $0.25 \pm 0.12$ | 1.57                   | 0.34                   |
| (5) chlorophyll                        | $2.12 \pm 2.16$                                              | $5.65 \pm 1.43$  | $0.44 \pm 0.53$ | 2.66                   | 0.21                   |
| (6) morphology                         | $1.83 \pm 2.32$                                              | $5.06 \pm 1.87$  | $0.99 \pm 0.70$ | 2.76                   | 0.54                   |
| (7) Total mutation frequency           | $7.73 \pm 6.06$                                              | $16.62 \pm 3.28$ | $1.47 \pm 1.22$ | 2.15                   | 0.19                   |

Table 4. Irradiation effect per rad of the three components of dose: gamma contamination ( $k_\gamma$ ), nitrogen ( $k_N$ ) and boron ( $k_B$ ) capture reactions.

$^\dagger$  Confidence limit ( $P=0.80$ )  $1.07 < \frac{k_N}{k_\gamma} < 3.00$  and  $0.07 < \frac{k_B}{k_\gamma} < 0.29$  char. 1.

$^\ddagger$  Confidence limit ( $P=0.80$ )  $0.77 < \frac{k_N}{k_\gamma} < 7.64$  and  $0.03 < \frac{k_B}{k_\gamma} < 1.13$  char. 2.

The other characters have no confidence limit. Units as in table 3.

difference in effect between treatments with active and inactive isotopes was related to the actual effect of irradiation expected in natural conditions (table 5):

$$\text{relative effect of nitrogen control} = \frac{k_N(495-13)}{k_\gamma 557 + k_N 495 + k_B 299},$$

$$\text{relative effect of boron control} = \frac{k_B(1376-75)}{k_\gamma 557 + k_N 495 + k_B 299}.$$

|                                     | Relative effect of isotope control |          |                     |          |
|-------------------------------------|------------------------------------|----------|---------------------|----------|
|                                     | Nitrogen<br>(per cent)             | $P$      | Boron<br>(per cent) | $P$      |
| (1) Reduction in seed-set           | 55.6                               | $< 0.01$ | 12.6                | $< 0.01$ |
| (2) Frequency of mutant individuals | 54.7                               | $< 0.01$ | 18.3                | 0.12     |
| (3) Mutation frequency: anthocyanin | 53.8                               | $< 0.01$ | 9.3                 | 0.49     |
| (4) hairiness                       | 52.7                               | $< 0.01$ | 31.1                | 0.06     |
| (5) chlorophyll                     | 66.2                               | $< 0.01$ | 14.0                | 0.42     |
| (6) morphology                      | 63.8                               | 0.02     | 33.7                | 0.18     |
| (7) Total mutation frequency        | 61.8                               | $< 0.01$ | 14.7                | 0.25     |

Table 5. Effect of radiosensitivity of a control of isotopic composition, i.e. difference of radiosensitivity in presence of  $^{15}\text{N}$  versus  $^{14}\text{N}$  or  $^{11}\text{B}$  versus  $^{10}\text{B}$  relative to radiosensitivity in natural conditions. Units as in table 3.

The chosen basis of reference (denominator) is here natural conditions, and not treatment with inactive isotope as it was in the previous experiment where only one element was controlled (Ecochard and de Nettancourt 1969): the relative boron effect should therefore be slightly lower here. It varies between 9 and 33 per cent, which agrees with the previous findings, but is significant for two criteria only in the present case.

In contrast, the relative nitrogen effect exceeds 50 per cent for all criteria and is highly significant.

#### 4. Discussion and conclusion

This experiment clearly demonstrates a high contribution of the capture reaction  $^{14}\text{N}(\text{n}, \text{p})^{14}\text{C}$  to genetic damage induced by thermal neutrons. This reaction was shown to contribute between a half and two-thirds of the total irradiation effect in normal conditions. This effect has not previously been directly demonstrated, but this was made possible by substituting  $^{15}\text{N}$  for the natural nitrogen in the material.

Nitrogen and boron reactions exert an independent and additive influence on the genetic expression of radiation injury. The nitrogen effect is greater than the boron effect for the following reasons:

(1) Greater abundance of the element, which more than compensates for the difference in cross-section and in specific energy.

(2) Larger effect induced per rad for the nitrogen reaction than for the boron reaction.

Direct comparison of thermal neutrons with 'Bremsstrahlung' is often expressed in the literature by the number of neutrons per  $\text{cm}^2$  producing the same biological damage as one rad x- or  $\gamma$ -rays. For instance Bora in a review (1961) mentions values between 0.2 and  $18 \times 10^9$  with an average of  $1 \times 10^9$ . Here values in normal conditions ( $^{14}\text{N}$  and natural boron) would lie between 3.4 and  $5.3 \times 10^9$ , which falls between the limits he mentions. The present calculation also gives the corresponding energy deposited by each radiation component.

The ratios  $k_{\text{N}}/k_{\gamma}$  and  $k_{\text{B}}/k_{\gamma}$  give an indication of what the relative biological effectiveness (RBE) of the two capture reactions was in the present conditions. The values found (table 4) are fairly consistent in spite of the relatively large standard deviations affecting  $k_{\gamma}$ ,  $k_{\text{N}}$  and  $k_{\text{B}}$ . For two criteria, namely reduction in seed-set and frequency of mutant individuals, confidence limits of the RBE values could be calculated by Fieller's theorem at 0.80 probability level (table 4, caption).

The low RBE ( $< 1$ ) observed for the  $^{10}\text{B}$  reaction is doubtless due to a larger concentration of boron in the cell membrane than in the nucleus, as previously suggested by Ecochard (1968) and Ecochard and de Nettancourt (1969). The difference could well be still more extreme in pollen grains, which already manifested similar boron effects (Ecochard and de Nettancourt 1969), than in microsporocytes where a RBE of no more than 2.18 was calculated (Ecochard 1968).

For the  $^{14}\text{N}$  reaction this reduction effect would not be expected: pollen contains little water and the rather high nitrogen content probably reflects a more even distribution.

RBE values of similar magnitude to those found here have been proposed for pure protons (Moutschen *et al.* 1969), although we know that many factors, physical and biological, influence the level of RBE. Moreover we must remember the bipartite structure of the  $^{14}\text{N}$  reaction: a proton is emitted, with a 0.59 MeV energy and a LET of 45 keV/ $\mu\text{m}$ , and a  $^{14}\text{C}$  nucleus recoils with an energy of 0.042 MeV only and a very short track. However, the recoil effect is certainly strong enough to break chemical bonds, and especially create direct injuries to the DNA molecules. Therefore calculations of the different sources of energy absorbed upon irradiation should take this into account, and the components for calculation of RBE should ideally be broken down further into their ultimate elements.

The working hypothesis in all our calculations was that for each component of the beam the effect of dose was linear. A more exact model includes the first and the second power of dose in an exponential relationship (Neary 1965). But this model approaches linearity with high-LET radiations (Neary and Savage 1966), which is the case for protons and alpha particles, and also with gammas when the dose-rate and the total dose are low as they are here.

In conclusion, there is some advantage in the approach by isotopic replacement of nitrogen and boron, and hence in the relative 'radiation transparency' which can be obtained in the material: the effects of charged particles released by the two processes of neutron capture can be compared directly with each other and with the gamma component of the beam. Although the gamma dose has only one value, certain conditions are fulfilled for a valid evaluation of each component: similar material, simultaneous irradiation, and therefore identical conditions of exposure.

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L'effet génétique de la réaction nucléaire  $^{14}\text{N}(n, p)^{14}\text{C}$  a été étudié dans un croisement de tomate; du pollen sec, ayant une composition chimique connue, a été soumis à un flux de neutrons thermiques de  $4,1 \times 10^7 \text{ n cm}^{-2} \text{ sec}^{-1}$ , plus 11,6 rads de contamination gamma. Dans ce but les plantes avaient été cultivées depuis le début de leur croissance sur du  $^{15}\text{N}$  au lieu de  $^{14}\text{N}$ .

Pour sept critères de radiosensitivité (réduction de la fertilité en graines et fréquences de mutations en  $F_1$ ) l'effet de la radiation s'est trouvé réduit d'un facteur de  $\frac{1}{2}$  à  $\frac{2}{3}$  comme conséquence de cette modification.

Comme la deuxième réaction de capture,  $^{10}\text{B}(n, \alpha)^7\text{Li}$ , était contrôlée d'une manière analogue dans le même matériel, on a pu comparer l'effet génétique des deux réactions. On les a trouvées indépendantes et additives, la réaction de capture par l'azote étant la plus importante, notamment parce qu'elle produit un effet par rad plus élevé.

La composante gamma de l'irradiation a fourni par ailleurs une base pour l'évaluation de la EBR. Celle-ci serait, dans les conditions présentes, au voisinage de 1,5 à 3,0 pour la réaction avec  $^{14}\text{N}$ .

Die genetische Auswirkung der Kernreaktion  $^{14}\text{N}(n, p)^{14}\text{C}$  wurde bei einer Kreuzung von Tomaten studiert; dabei wurde der trockene Blütenstaub, dessen chemische Zusammensetzung bekannt war, thermischen Neutronen einer Fluxdichte von  $4,1 \times 10^7 \text{ n.m}^{-2} \text{ sec}^{-1}$  bei einer Gamma-Kontamination von 11,6 rads ausgesetzt. Für diese Untersuchung wurden die Pflanzen vom Beginn ihres Wachstums statt auf  $^{14}\text{N}$  auf einer Grundlage von  $^{15}\text{N}$  gezogen.

Für sieben Kriterien der Strahlenempfindlichkeit (Verminderung der Samenbildung und Mutationsfrequenzen in  $F_1$ ) reduziert diese Veränderung der Aufwuchsbedingungen den Strahleneffekt auf die Hälfte bis auf zwei Drittel.

Da die zweite Einfangreaktion,  $^{10}\text{B}(n, \alpha)^7\text{Li}$ , auf ähnliche Weise und mit demselben Material überprüft wurde, ließ sich die genetische Auswirkung beider Reaktionen vergleichen. Es wurde gefunden, daß sie abhängig und additiv waren, wobei die Einfangreaktion des Stickstoffs die wichtigere war, teilweise weil mit ihr eine höhere Wirkung pro Rad erzielt werden konnte.

Die Gamma-Komponente der Bestrahlung erlaubte auch eine Bestimmung der RBW. Sie liegt unter den gegebenen Verhältnissen für die Reaktion mit  $^{14}\text{N}$  bei 1,5 bis 3,0.

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